

Extra-galactic spectral lines - SWG Summary (key science concepts)

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On behalf of the ex-gal spectral line SWG

This SWG areas

- 'New' SWG
 - But long history of science in this area
 - Many important astrophysical line tracers beyond H1 21-cm
 - Uniquely trace different material/environment = different science
 - From high-redshifted lines to local universe probe of physics
 - Success of instruments like ALMA underline the crucial nature of such traces
 - Band 5+ provide critical new science capabilities in this area.. This SWG is a strong advocate of increased frequency range/capability

Science discussion areas

Our Aims:

- Discussion focus on 'key science concepts (KSCs)' rather than projects - **Start this process here and take this back to the wider group many of which not here.**
- Explore commensality and science goal synergies with other areas

Broad science areas/drivers (non-exhaustive)

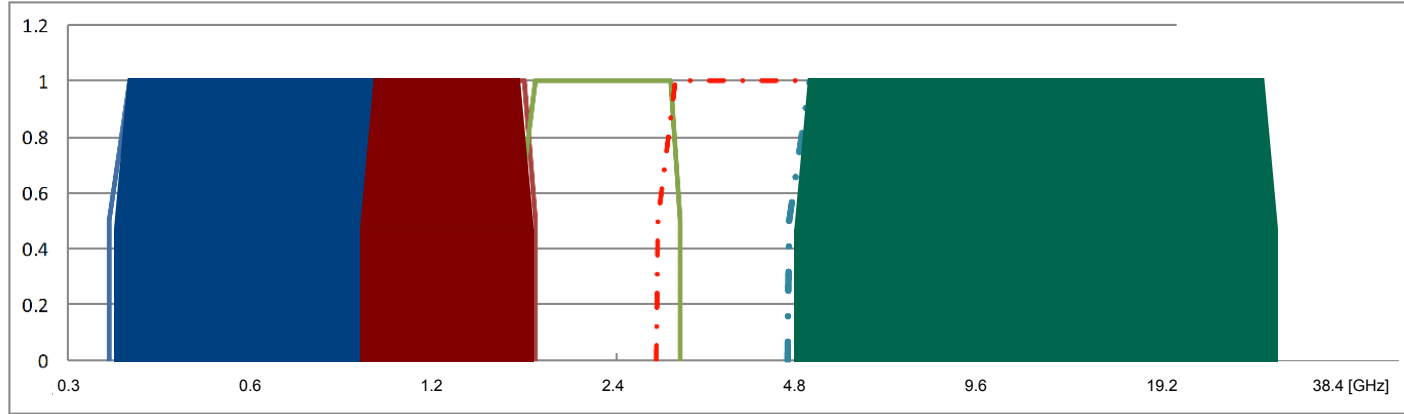
- Local group [SMC/LMC etc] – Galactic-type masers
- Local galaxies
 - Dense molecular gas traces & masers
 - RRLs
- Wide-area line Maser searches (OH/H₂O etc)
- High-z dense gas tracers
 - CO/CS/HCN etc, lensed lines [follow-up]

Commensality with other SWG/areas & science Synergies

- Two types here:
 1. Science synergies – different areas/techniques drive toward the same/similar/complementary science goals
 2. Commensality – different science goals but can utilise similar/same resource

Frequency coverage of main lines

SKA1-MID



ALMA



↑
OH masers

↑
OH masers*
↑
formaldehyde maser

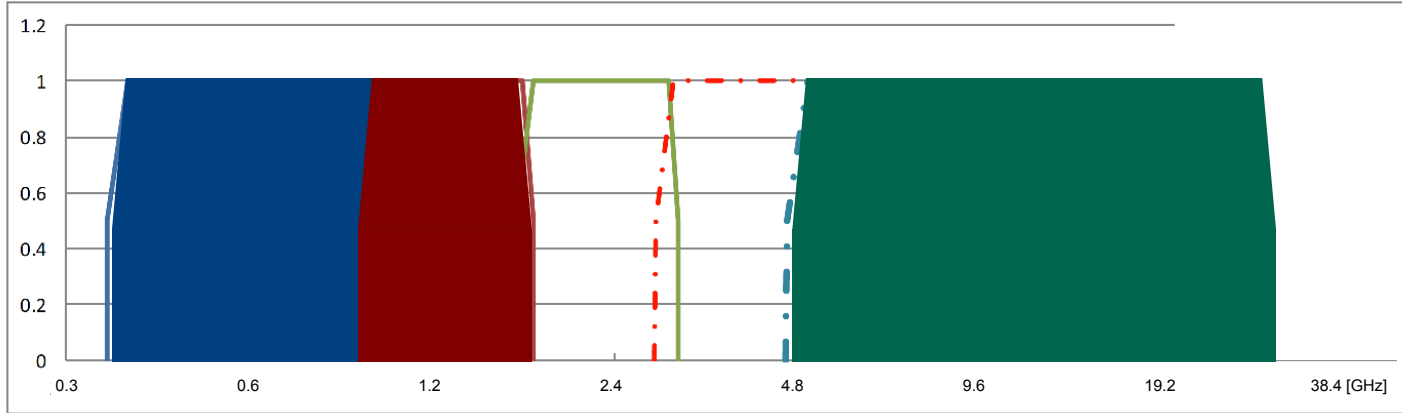
↑
OH masers*
↑
methanol maser

↑
methanol maser*

↑
H₂O maser

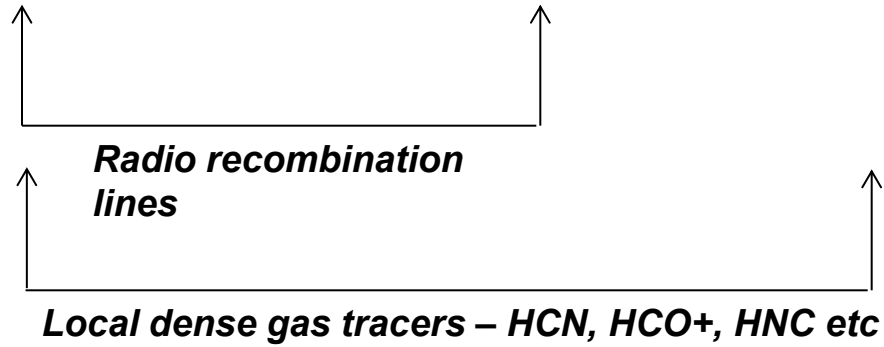
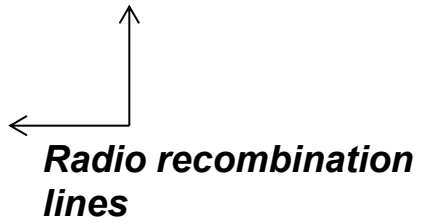
Frequency coverage of main lines

SKA1-MID



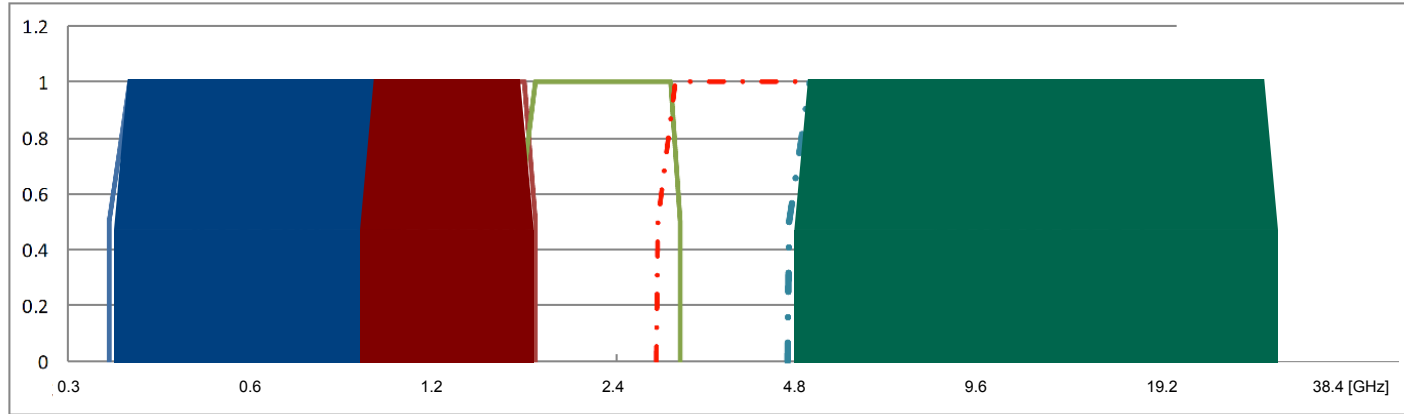
ALMA

0.3 0.6 1.2 2.4 4.8 9.6 19.2 38.4 76.8 [GHz]

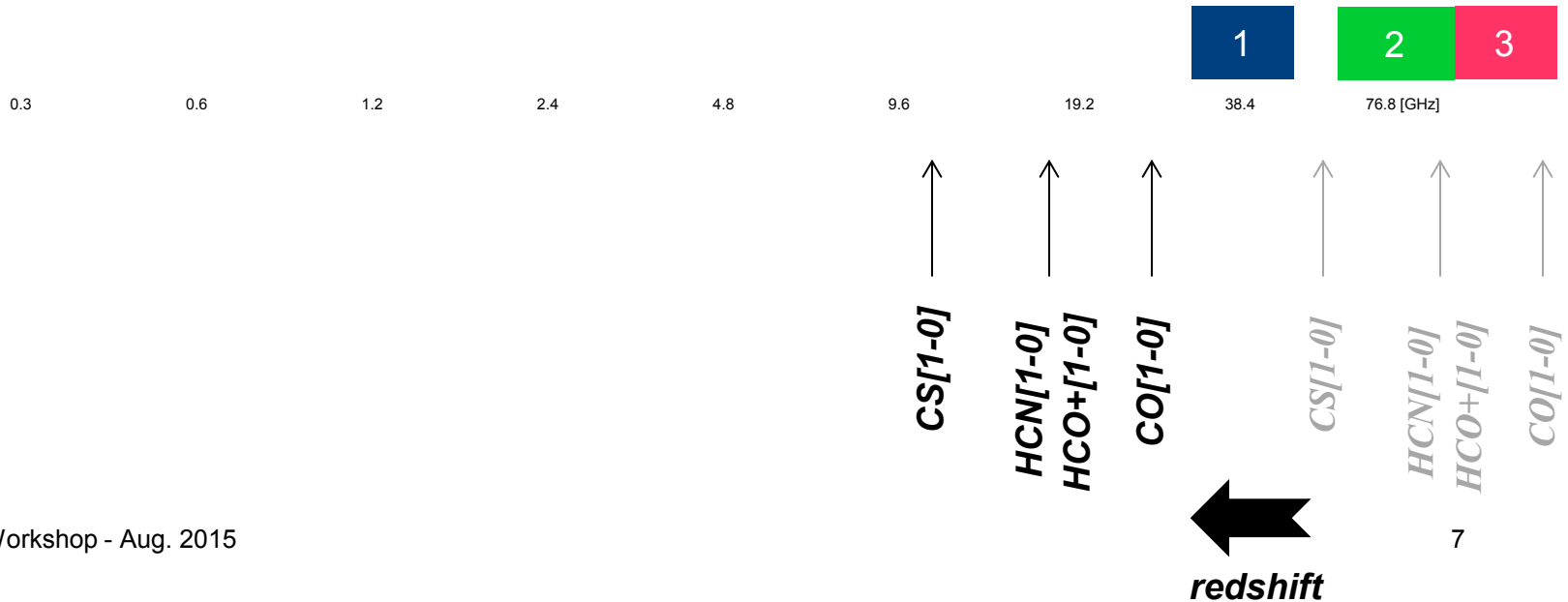


Frequency coverage of main lines

SKA1-MID



ALMA



Local universe KSC

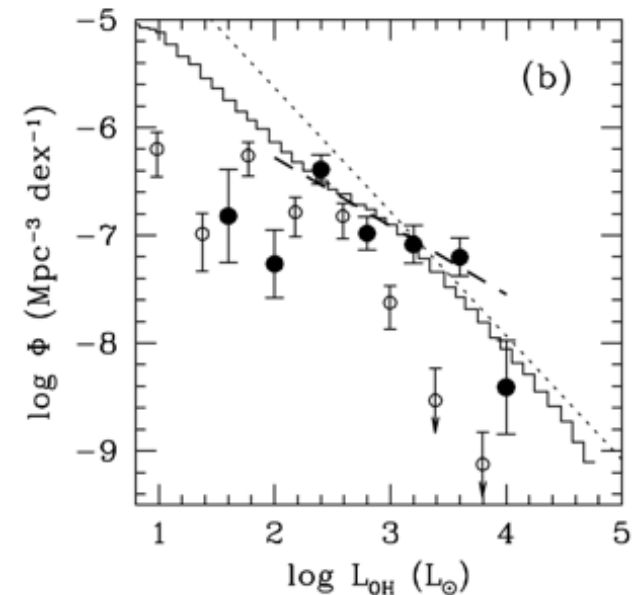
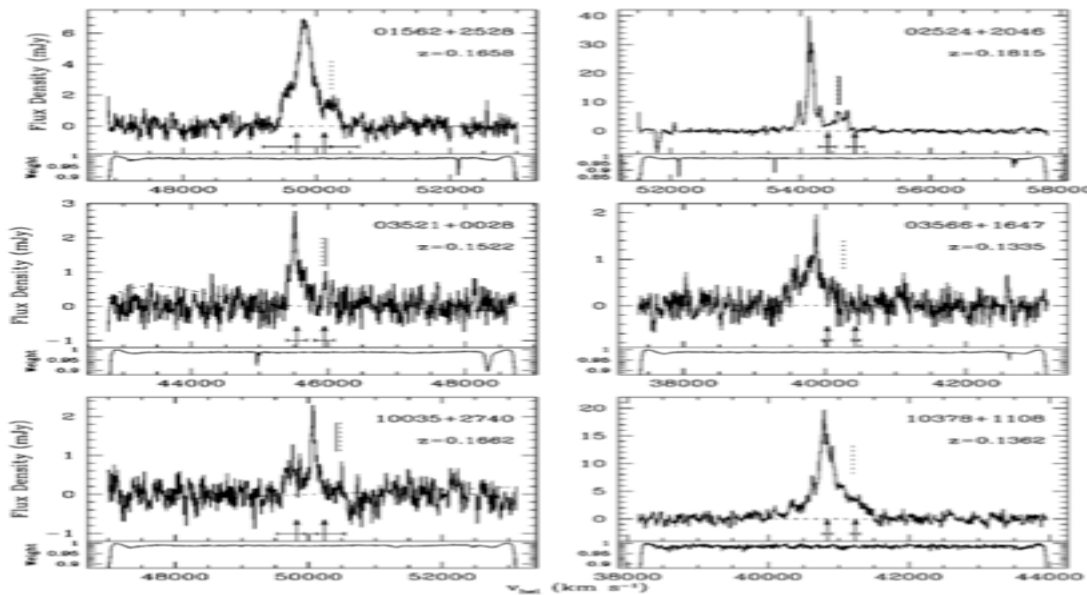
- Local galaxy survey - dense (star-forming) ISM in nearby Universe:
 - 'physical process' - linking Galactic studies through to local Universe and provide cornerstone for high-z interpretation - molecular gas a key component
 - Targeted observations of a statistical and representative sample of local galaxies - combined line & continuum
 - star-formation physics at physically important scales via probing the causes (dense gas) and consequences (continuum)
 - Band 2 (OH), Band 5(+) - dense gas tracers
 - Tuned to multiple dense gas tracers - HCN, H₂CO, HCO⁺ etc

Commensal/synergistic

- Science driver synergies –
 - Dense gas tracer as a key component in our understanding of local galaxies
 - Critical to studies of SFE and fuelling of activity
 - **Both science synergies & commensality** between multiple targeted surveys of local galaxies – e.g. continuum, magnetism, H1..

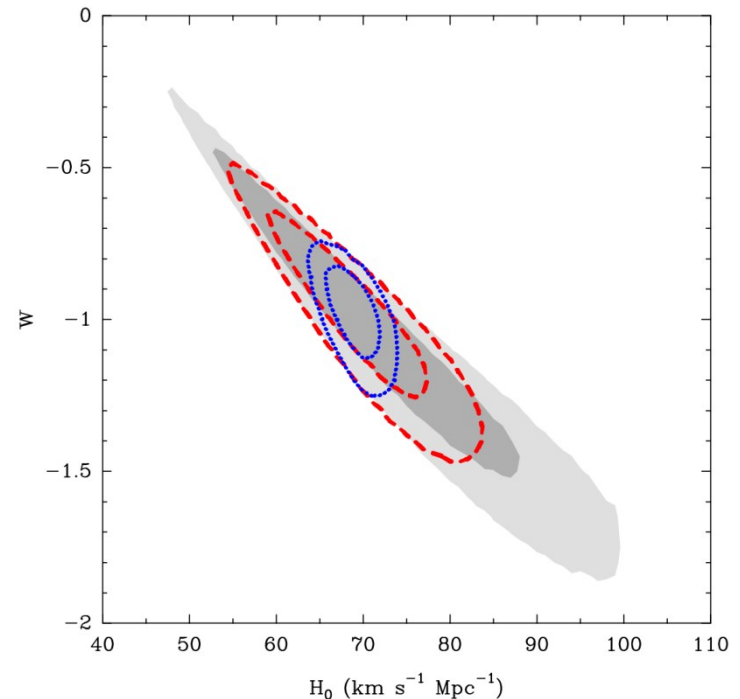
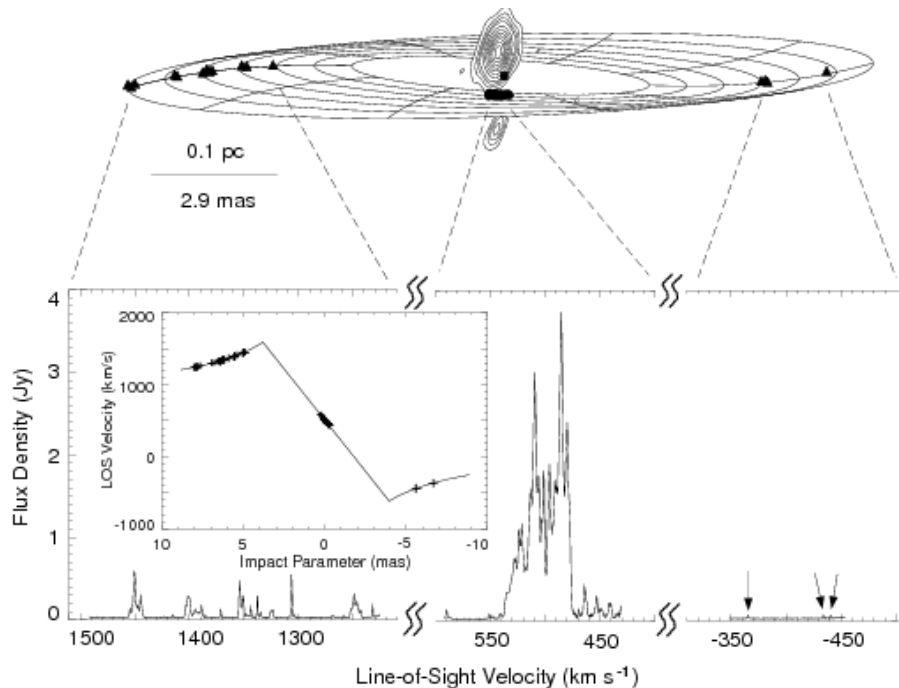
Wide area Maser searches KSC

- 1.667, 1.665 GHz hydroxyl search to find $\sim 10^4$ new MM and absorption systems at $z < 0.85$
 - What role does molecular gas play in the fueling of AGN?
 - What is the formation rate and evolution of the most extreme nuclear driven starbursts?
 - How do magnetic fields in distant galaxies evolve?
 - Does the fine structure constant vary?



Wide area Maser searches KSC

- 22.245 GHz water search to find MM systems at $z < 3.45$ (with Band5+)
- How does the black hole mass function / scaling relations vary with galaxy mass / type (black hole mass precision $\sim 10\%$)?
- What is dark energy?
- Needs VLBI capability (with high frequency component)



Commensal / Synergy

- Hydroxyl MM
 - Shallow luminosity function, wide better than deep
 - line widths ~ 150 km/s (~ 0.5 -1 MHz)
 - Carried out as part of the v.wide/all-sky survey (Band-2; SKA-MID)
 - Needs VLBI follow-up
- Water MM
 - Low detection rates (1/100) and at high frequency
 - Targeted observations of edge-on Seyfert galaxies (Band-5+; SKA-MID).
 - Needs VLBI follow-up at high frequency.
 - VLBI resolution may limit usable redshift range (except in the case of lensing).

High-z line KSC

- Deep field band-5(+) dense gas tracer search (CO/CS/HCN)
 - **Tracing the molecular gas luminosity function**, overall gas reservoir (ground-state CO), plus HCN/HCO+ dense, SF gas
 - **Cosmic evolution of molecular gas density**
 - **Chart SFE at high-z** – resolved KS – continuum+gas tracers
 - Band 5(+) can directly target ground-state (low-excitation) molecular gas at high redshift
 - (At $z > 6$ w/ SKA1, BAND 5+ \Rightarrow $z > 2.5$ w/ extension to 24 GHz)
 - ie. Resolving a variety low J dense gas tracer from $z \sim 2 \rightarrow 6$.
 - Single deep pointing – Commensal with deep continuum pointing (band 5(+))
 - Depth/fov advantages compared to pre-SKA surveys (e.g. JVLA Ka survey $1\sigma \sim 55 \mu\text{Jy}$ \rightarrow 6-sigma detection at knee of luminosity function.
 - SKA 10times $\Rightarrow \sim 1 \mu\text{Jy}$ sensitivity. Can also probe HCN/CS

Tracing the luminosity function

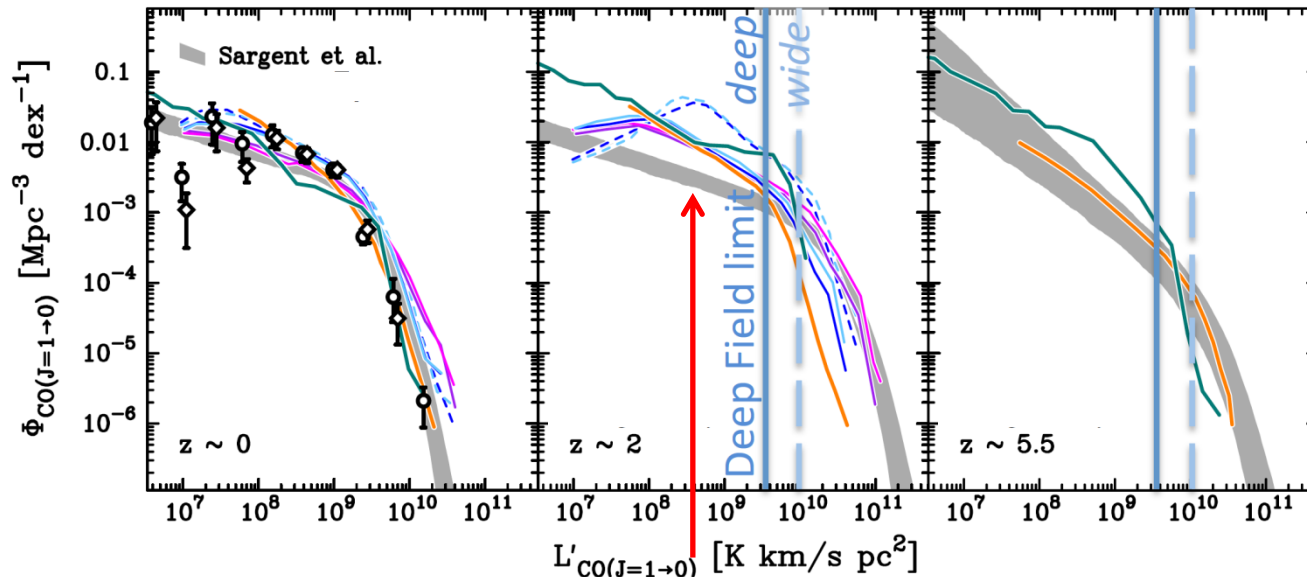
- Redshift ranges (3.8-5.1, 5.1-7.2 – CO[1-0]) (8.6-11.1, 11.1-15.5 – CO[2-1])
- Volumes sampled: approx. $3 \times 10^7 \text{ Mpc}^3$
- Indicative sensitivity required: 1uJy (approx. 10-fold improvement over current surveys)

observations ($z \sim 0$):

- ◊ Kereš et al. (2003)
- ★ Obreschkow & Rawlings (2009a)

numerical simulations:

- Obreschkow & Rawlings (2009b)
- Lagos et al. (2011)
- Duffy et al. (2012)
- Fu et al. (2012)
- Vogelsberger et al. (2012)



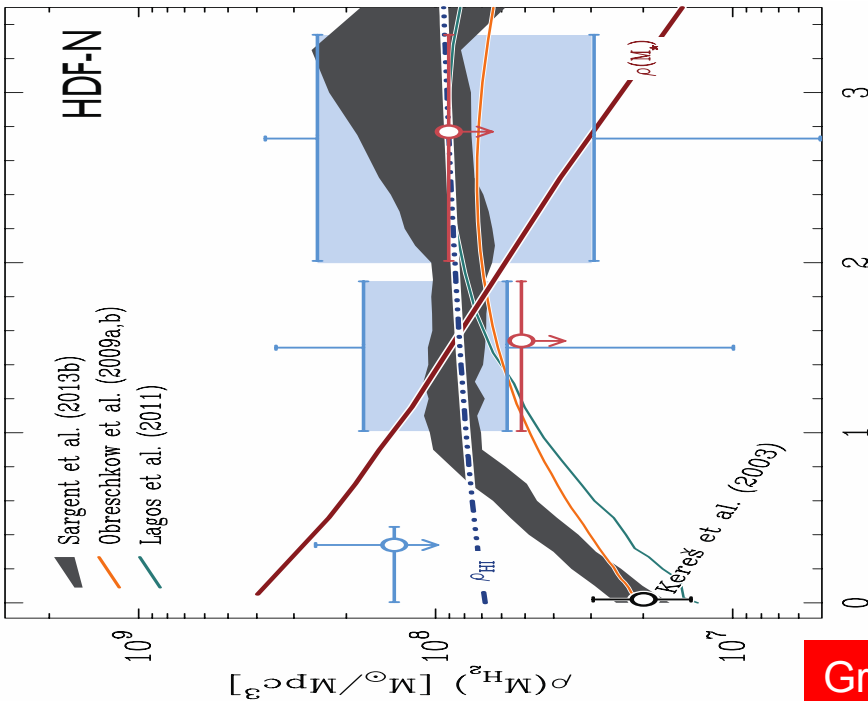
With SKA deep pointing

Towards a cosmic inventory of star-forming gas

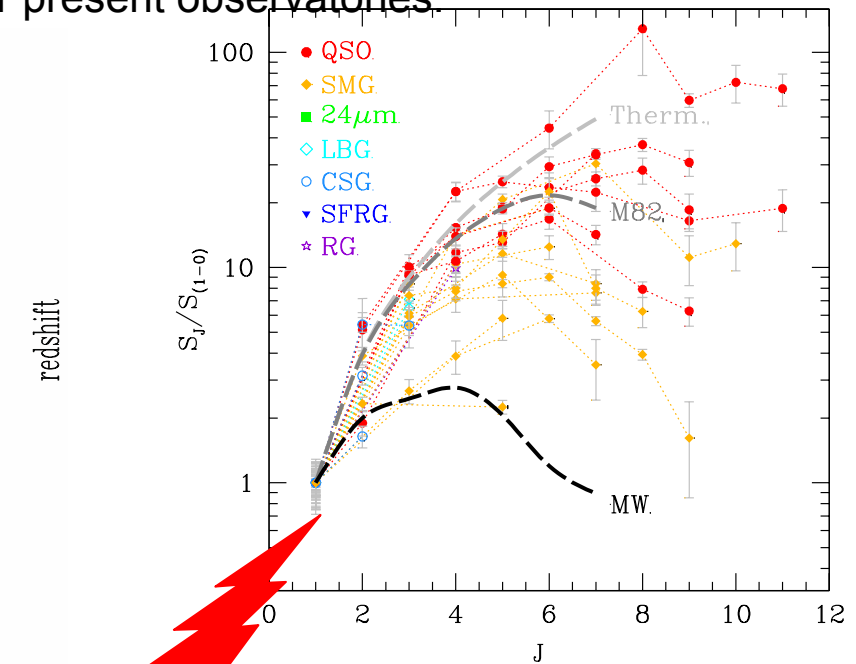
With blind PdBI, JVLA & ALMA line scan surveys we are beginning to sample CO luminosity function evolution and the “molecular Lilly-Madau plot” ...

Current mm-blind surveys ~100s hrs over very small fov (0.5arcmin²) - PdBI

... but, we really would like to do this based on the ground-state CO transition which is either not accessible or limited by sensitivity for present observatories.



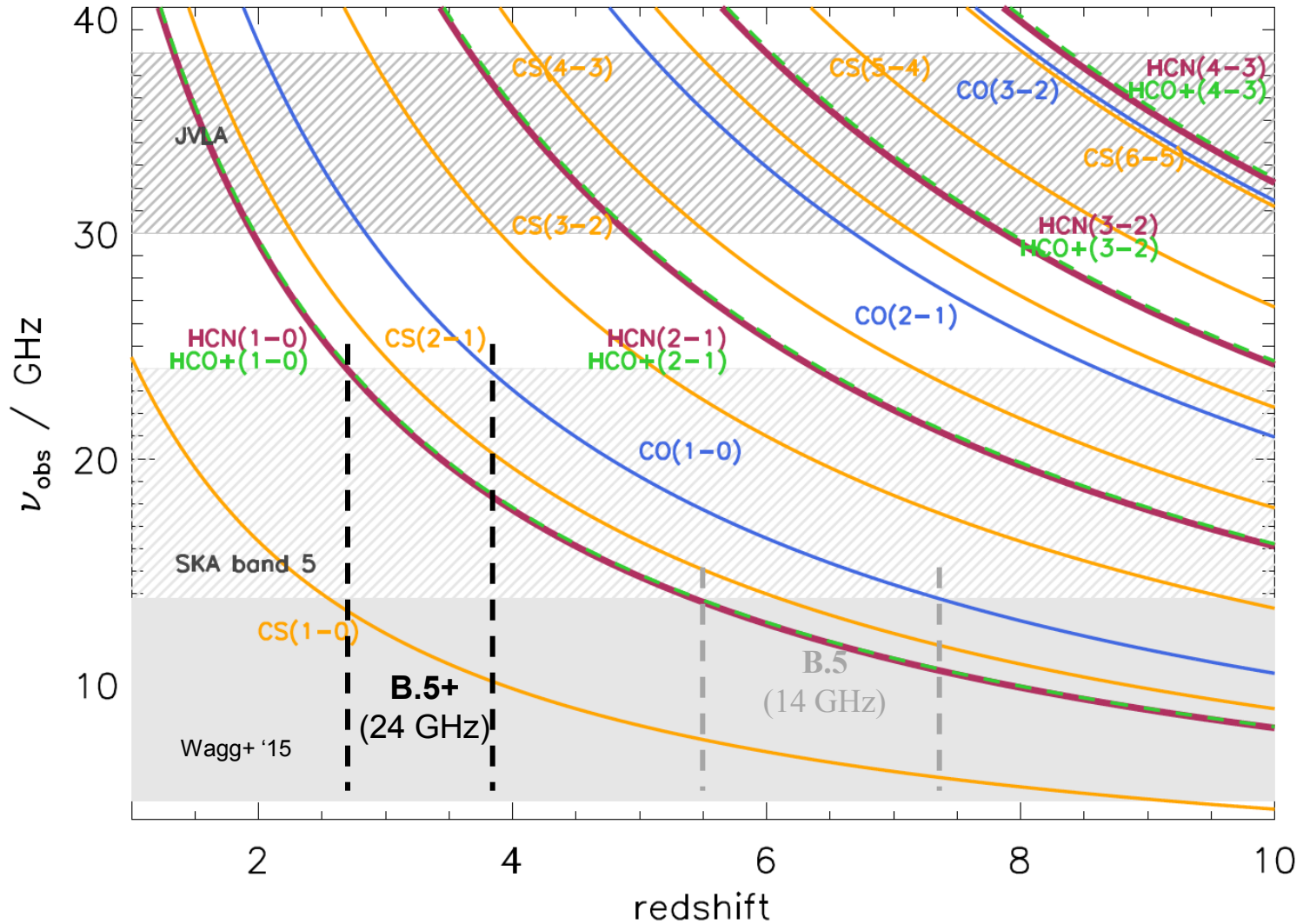
Walter+ '14; Decarli+ '14



Carilli & Walter '13

Ground-state CO → total molecular gas reservoir

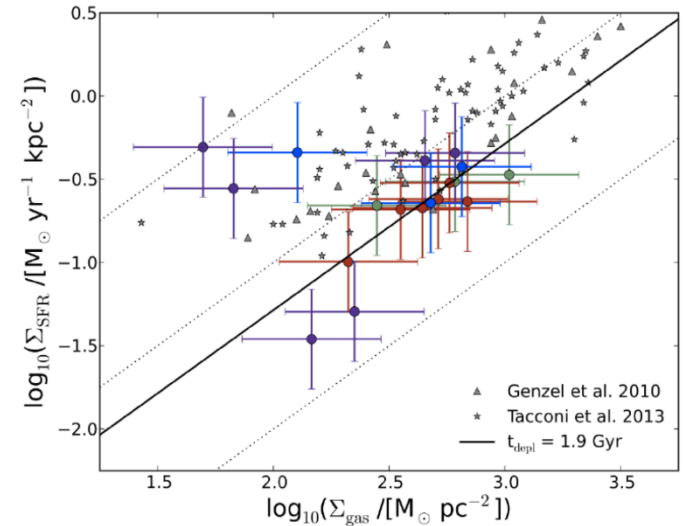
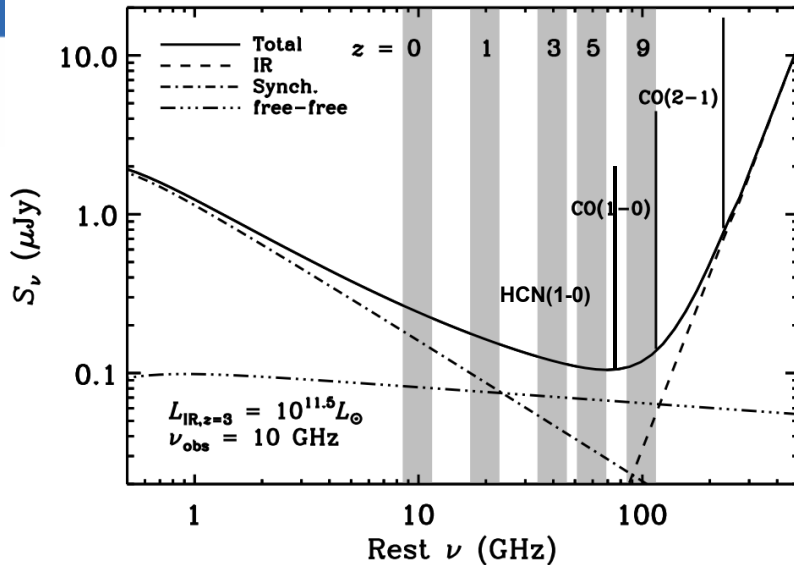
Molecular gas at high z w/ band 5(+): low- J transitions



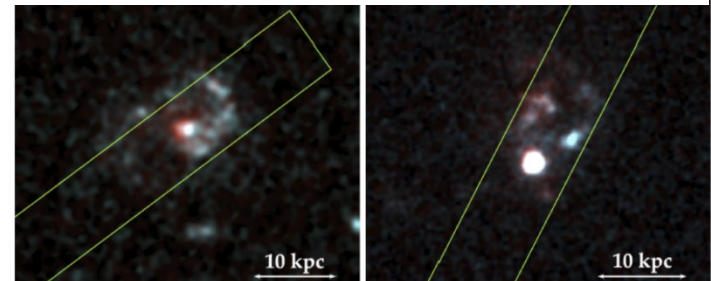
SKA band 5(+) – the key to SFE studies at high redshift

Band 5 can directly target ground-state (low-excitation) molecular gas at high redshift!
(At $z > 6$ w/ SKA1, at $z > 2.5$ w/ extension to 24 GHz.)

— Marginally resolved (8 kpc) Schmidt-Kennicutt relation in $z = 1.2$ galaxies:
➔ SKA could extend analysis to several 10s of resolution elements



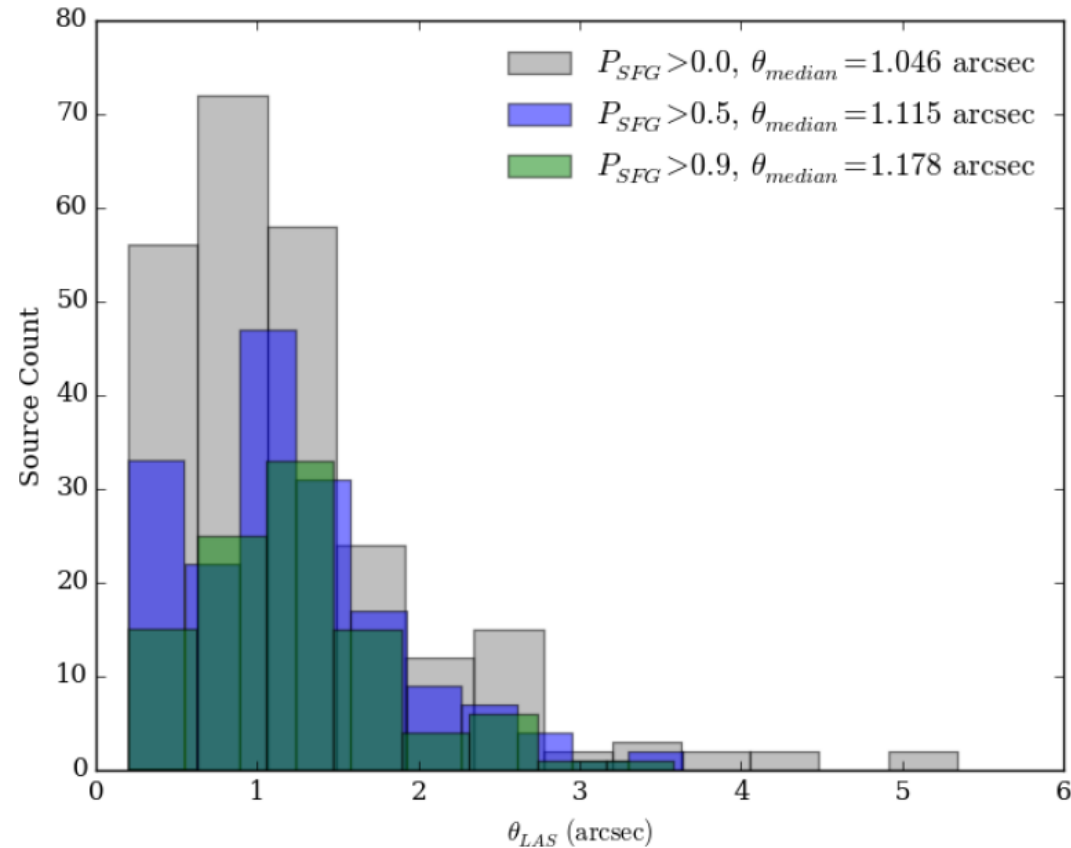
- $^{12}\text{CO}[1-0]$ ➔ overall molecular gas reservoir
- $\text{HCN}[1-0]$, $\text{HCO}^+[1-0]$ ➔ dense, star-forming gas
- $^{12}\text{CO}/^{13}\text{CO}$ ➔ e^- temp. in HII regions, IMF variations



Freundlich+ '13

Resolved μJy radio source population - continuum

- High resolution ($<0.5\text{arcsec}$) critical for component separation
- Typical angular size of μJy starformers $\sim 1-1.2\text{arcsec}$

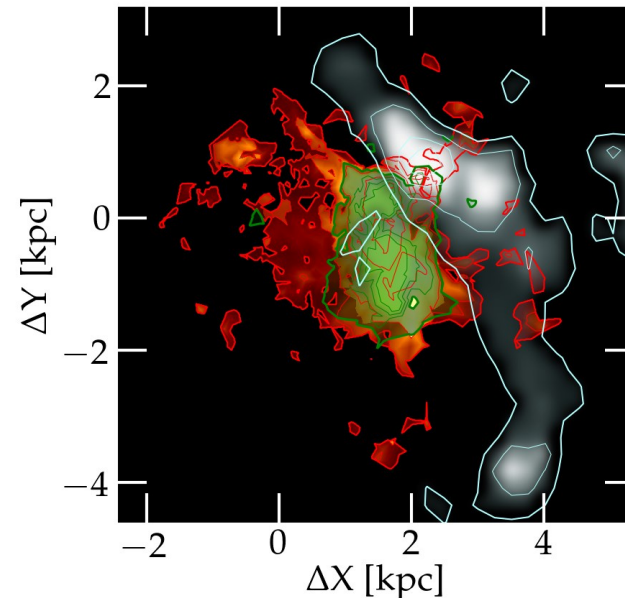


GOODS-N (e-MERLIN - 250 sources

Above local 5-sigma 10-20 μJy separated by starburst/AGN contribution – Wrigley 2015)

High redshift (lensed) Universe

- The total molecular gas content of galaxies at $z > 3.8$ at sub-100 pc-scales from CO (1-0) (with Band5+)
 - Directly measure star-formation using several tracers (KS-relation, Radio-FIR relation, Free-free emission)
 - Measure galaxy assembly (dynamics, out-flows, mergers) at EoR
 - Targeted observations of > 100 s lensed star-forming galaxies with complimentary ALMA and HST imaging at 100-200 mas resolution.
 - SKA2 science with SKA1
- Example of lensed SMG at $z \sim 3$
- 50-100 pc unlensed resolution
 - RED : CO (5-4) (ALMA)
 - GREEN: Heated dust (ALMA)
 - WHITE: UV-stellar emission (HST)
- SKA will add CO (1-0)



Summary

- Multiple KSC emerging.. [diverse, rapidly growing group and interests]
 - First f-2-f meeting of group this week
 - Early stage for group
 - Number of science areas/drivers yet to be discussed or represented at this meeting (not presented).
 - e.g. ammonia, methanol - accessible via band5(+)
 - Many cases still in development phase and not highlighted here
- Band clarifications required – line science dictated by band definition (or rather science should dictate band definition!)
 - Particular band 5 vs 5+ (or other)
 - Band 2 up to local OH..
- Not only high degree of commensality in many areas but high level of synergy in the science goals that needs to be developed..